

Determinants of climate change mitigation technology portfolio: An empirical study of major U.S. firms



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ABSTRACT

To cope with climate change, a firm can employ a portfolio of heterogeneous mitigation technologies, including pollution control, eco-efficiency, green design, low-carbon energy, and management system, each with distinct operational and climate implications. In this paper, we study how management factors of a firm can shape the structure of its climate change mitigation technology portfolio. Based on a sample of 362 major firms in the United States for 2011–2013, we find delegating the responsibility of climate change to a position higher in firm hierarchy can promote the use of green design technology. The provision of monetary incentive to firm management contingent on climate change performance is positively associated with the portfolio size, and the use of pollution control and eco-efficiency technologies. Non-monetary incentive such as recognition is effective in stimulating the use of eco-efficiency technology. The firm's risk attitude towards climate change negatively affects the proportion of eco-efficiency technology in the portfolio. The results underscore that firms should take differential effects of management factors on technology portfolio into consideration when building the portfolio to attain desired economic and climate outcomes.

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1. Introduction

Climate change caused by greenhouse gas (GHG) emissions has emerged as one of the greatest environmental, economic and social challenges facing human society (Volk, 2008). To address the challenge, the United Nations Environmental Program calls upon firms worldwide to change the profit-oriented management practices and adopt climate change mitigation technologies (CCMTs) to control GHG emissions and limit the increase in global mean temperature to 2 °C (IPCC, 2014). Here we refer “climate change mitigation technology” to the technology developed to reduce the hazards of GHG emissions. In reality, a firm can employ a combination of different CCMTs. These technologies constitute the firm's climate change mitigation technology portfolio (CCMTP). As one of many examples, Coca-Cola reports that the firm has responded to climate change by phasing out diesel fleet with renewable trucks,

improving the energy efficiency of the manufacturing process, and redesigning the products to reduce carbon footprints (Coca-Cola, 2015). PepsiCo, as Coca-Cola's main competitor, employs a different CCMTP. Rather than using renewable trucks, PepsiCo stresses that it reduces transportation emissions by shipping products via trains and vans, which are more fuel efficient than trucks (PepsiCo, 2016). The comparison between Coca-Cola and PepsiCo gives rise to the question: why do the firms configure their CCMTPs in different ways? Are there any factors that can explain the different compositions of CCMTPs? We aim to answer these questions through this research.

Have a proper mix of technologies is critical for a firm to attain economic and environmental goals (King and Lenox, 2002). A lot of studies have examined the impacts of the technology portfolio on firm performance. There is abundant evidence that because each type of technology has its distinct impact on a firm's economic and environmental performances, the effect of the portfolio hinges on its composition (Klassen and Whybark, 1999; Wang, 2018, 2017). On the other hand, a burgeoning stream of literature has investigated the management factors behind the use of environmental technologies. The management factors studied include but are not

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limited to management attitude (Nakamura et al., 2001), responsibility delegation (Martin et al., 2012), and incentive policy (Fabrizi et al., 2014; Mahoney and Thorn, 2006). However, prior research focuses predominantly on the management factors behind a specific type of technology, such as energy efficiency, green design, and renewable energy. None of the existing studies examines the managerial driving force behind the technologies from the portfolio perspective. Therefore, it is unclear how management factors can affect the way a firm allocates resources to different technologies. This paper aims to close the gap in literature by analyzing the connection between the composition of CCMTP and several prominent management factors.

To carry out the study, we collect the information on the United States (U.S.) firms' climate change strategies from the CDP database (<http://www.cdp.net>), formerly known as the Carbon Disclosure Project. As the world's largest database on firm climate strategy, CDP aims to transform the way the world does business to prevent dangerous climate change and protect the world's natural resources. CDP has incentivized thousands of firms and cities around the world to measure and disclose their climate information. Our research focuses on 362 major U.S. firms in the period of 2011–2013. Drawing on literature and CDP data, we are able to identify five types of technologies, i.e., pollution control, eco-efficiency, green design, low-carbon energy, and management system. We study and discuss differential effects of responsibility delegation, incentive policy and risk attitude on CCMTP.

The remainder of the paper is organized as follows. Section 2 introduces the typology of CCMTs and the management factors of interest in this study. Section 3 presents our research framework, and motivates the relationships between management factors and CCMTP. Sections 4 and 5 describe the data, variable construction, methodology and the empirical results. In Section 6, we conclude and explore managerial insights of this research.

2. Typology of climate change mitigation technologies

A tremendous growth in climate change awareness is fueling the need for employing various CCMTs, including the installment of GHG capture equipment, efficient use of energy and materials (Petek et al., 2016), replacement of conventional energy with low-carbon energy (Arvizu et al., 2011), green product design (Sihvonen and Partanen, 2017), and deployment of environmental management systems such as employee training and emission reporting (Jira and Toffel, 2013).

Previous research has proposed different ways to classify CCMTs into exhaustive and mutually exclusive types. The most common approach is to designate environmental technologies into management system, pollution prevention, or pollution control (King and Lenox, 2002). The management system technologies change the way operations are managed, such as GHG monitoring and reporting, training employees and setting emission goals. The pollution prevention technologies reduce or eliminate the creation of pollutants by modifying existing processes or products. Typical pollution prevention technologies include building or process energy efficiency, product redesign with environmentally friendly materials, and low-carbon energy. The implementation of pollution prevention technologies requires structural investments in cleaner technologies. The pollution control technologies, also dubbed as end-of-pipe (EOP) technologies, capture, treat, and dispose of pollutants by adding cleaning equipment and procedures at the end of existing process, without interferences with the existing processes or products. Typical pollution control technologies involve burning, recycling, filtering and catalyzing the pollutants. While this three-category typology captures main distinctions of different

technologies, a more fine-grained classification is desirable. For instance, under the conventional three-category typology, renewable energy and energy efficiency both belong to the category of pollution prevention technology, because they forestall the creation of pollutants. However, renewable energy and energy efficiency are vastly different technologies, so labeling them as pollution prevention would mask their differences. Therefore, in this study we propose to further classify pollution prevention technology into three types of technologies: eco-efficiency, green design, and low-carbon energy. These three technologies combined with pollution control and management system constitute the five types of technologies employed in our study. We note that similar classification has been adopted in Sharma and Henriques (2005) for the environmental technologies employed by the forest industry. Below we describe the five CCMTs. For further details and examples of CCMTs, we refer the readers to Wang (2018).

Eco-efficiency technologies aim at reducing carbon emission by cutting the amount of energy and material input required for the same level of output or service (Kang and Lee, 2016). Eco-efficiency technologies belong to the general category of preventive approach that reduces emissions before they are generated.

Green design technologies encompass activities aiming to reduce the carbon footprint of the products through design change, typically by replacing carbon-intensive materials with sustainable ones and making the products more energy efficient and easier to recycle. We note that green design technologies target at the products whereas eco-efficiency technologies target at the processes.

Low-carbon energy technologies are mainly implemented to replace the conventional energy sources such as coal and oil by clean energy sources such as solar, wind and biofuel. Firms acquire the clean energy by either installing the energy generation units themselves or purchasing in the market.

Pollution control technologies, also referred to as "end-of-pipe" technologies, capture, treat, and dispose of pollutants by adding cleaning equipment and procedures at the end of existing processes. Typical pollution control technologies include end-of-pipe combustion or recovery of methane, and catalytic decomposition of N₂O and hydrofluorocarbons (Frondel et al., 2007).

Management system technologies reduce GHG emissions by adapting the way operations are managed (Klassen and Whybark, 1999). In contrast with other technologies, management systems primarily comprise of soft approaches that promote engagement with the climate change issue through organizational innovations. Typical management system technologies include GHG monitoring and reporting, and training employees to raise climate change awareness.

3. Management factors and climate change mitigation technology portfolio

Fig. 1 illustrates our research framework which relates firms' management factors to CCMTP. The management factors under investigation include responsibility delegation, incentive policy and risk attitude. We model the portfolio with both comprehensive measures like overall size and compositional measures like proportion of investment in each technology. The following subsections elaborate on the logic and motivation of the relationships proposed in the model.

3.1. Impact of management factors on CCMTP size

Numerous studies have shown that support and commitment from the management are critical for creating a supportive climate and providing adequate resources for the introduction of new

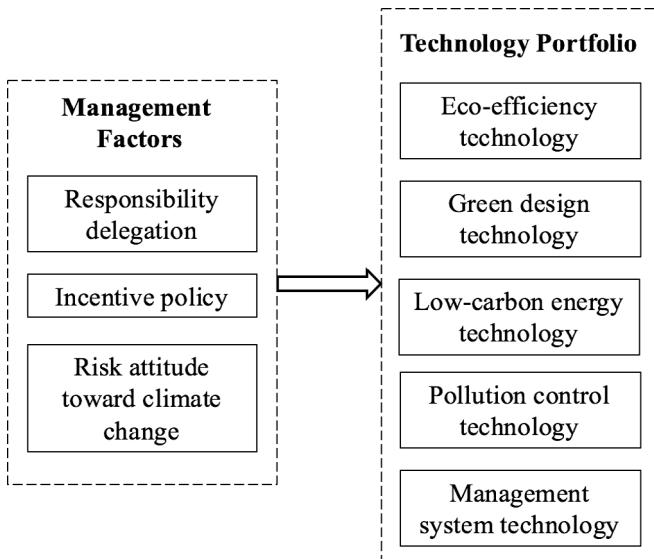


Fig. 1. Research framework.

technologies (Gibson and Birkinshaw, 2004). In our paper, we consider three major management factors: (i) responsibility delegation, (ii) incentive policy, and (iii) risk attitude towards climate change. The theory of resource-based view supports the use of these three factors. Galende and de la Fuente (2003) point out that an organization has both tangible and intangible resources that impact innovation and technology investment. Tangible resources include an organization's size and debt and intangible resources consist of organizational sources and human sources. The management factors are closely related to the intangible resources. Moreover, some empirical studies suggest that management factors have a positive influence on technology innovation (Canto et al., 1999). In addition, when adopting climate change mitigation technologies, one of the major risks is firm-specific risk that is closely related to organization management. That is, if the managers do not demonstrate interest in adopting climate change mitigation technologies or act too slow in adoption, the effectiveness of climate change mitigation technologies can be adversely affected (Benaroch, 2002). Therefore, the three factors of responsibility, incentives and risk attitude are essential to guarantee the adoption of new technologies and are supported by resource-based view because whether companies have right technology portfolio is really dependent on the right management factors.

In what follows, we discuss specific management factors and the possible mechanisms through which these management factors may affect the size of CCMTP.

3.1.1. Responsibility and CCMTP size

While many firms recognize the importance of climate change, the ways they manage the challenge vary. Specifically, different positions that assume direct responsibility for climate change may carry different weights over technology adoption decision. In reality, we observe that climate change mitigation programs are delegated to different management levels by firm leadership. For instance, in 2013, Smithfield Foods reports to CDP survey that the firm delegates the climate change issue to its Employee and Public Responsibility Committee. General Motors indicates that its Public Policy Committee of the Board of Directors is responsible for climate change issues. Coca-Cola assigns the responsibility to Chief Sustainability Officer. Schlumberger delegates the responsibility to Vice President of Corporate Development. Therefore, the direct

responsibility for mitigating climate changes fall into different levels of administrative hierarchy.

We reason that a higher position in the firm hierarchy is associated with better accesses to resources, information and capital. A higher position is also naturally endowed with better capability to coordinate and communicate the activities across various functional departments. Therefore, we posit that the position of direct responsibility for climate change in the firm hierarchy is indicative of management commitment towards the issue. A higher position implies that the firm is likely to implement a larger climate change technology portfolio.

3.1.2. Incentive policy and CCMTP size

Prior researches have shown experimental evidence that setting appropriate incentives can promote desired individual efforts and performances (e.g., Prendergast (1999), Lazear (2000), and references therein). In the environmental management literature, empirical studies report both positive and negative relationships between CEO's compensation (e.g., salary, bonus, stock options) and environmental performance (McGuire et al., 2003). But few papers have ever studied the impact of environment-oriented incentives on environmental performance. Only recently does the effectiveness of explicit monetary incentives paid to general middle-level to high-level management positions in promoting environmental sustainability come under investigation. Merriman and Sen (2012) show that direct monetary incentives to middle-level management increase sustainability initiatives.

In reality, a firm may provide monetary and/or non-monetary incentives to reward activities promoting sustainability improvements within the firm. Unlike the base salary, these incentives are typically contingent on performance. For instance, General Motors reports in 2013 that the firm provides monetary incentives to the executive team, business unit managers, energy managers and employees for attaining energy saving and carbon footprint reduction goals. Kellogg Company reports that in 2013 that the performance pay of CEO, business unit managers and facility managers is linked to achievement of energy, GHG and water use reduction goals. Hence based on the academic findings and practices in the firms, we propose that monetary incentive for climate change performance is positively related to the size of CCMTP.

Previous research suggests that non-monetary incentives can lead to improved job motivation and performance (Gale, 2002). For example, General Motors has used non-monetary incentives such as recognitions or awards to motivate all employees to follow energy use criteria in their performance evaluation. Kellogg Company awards employees through nomination for W.L. Kellogg Values Award. We hence expect that the provision of non-monetary incentive policies will increase the implementation of climate change mitigation technologies.

3.1.3. Risk attitude and CCMTP size

Mounting climate change pressure creates emerging risks to business, including regulatory risk (Kim et al., 2015), reputational risk (Arora and Lodhia, 2017), and physical climate change risk (Thomas et al., 2004). In this paper, we aggregate regulatory risk, reputational risk and physical climate change risk into a single risk measure. The aggregation is supported by Murillo-Luna et al. (2008), which suggest that the stakeholders' pressure perceived by managers can be analyzed across a single dimension. Specifically, they find that "firms do not respond selectively to the different stakeholder groups, but they respond to all of them in a similar way." Therefore, regulatory and reputational risks, although originated from different stakeholder groups such as government and customers, can be aggregated to form a single demand function for environmental protection. In addition, physical environment

can also be regarded as stakeholder (Haigh and Griffiths, 2009), so physical climate change risk can be integrated with regulatory and reputational risks to form a single risk measure. Early empirical studies find a positive impact of regulatory pressures on the usage of environmental technologies (Reid and Toffel, 2009). The pressures from consumers also exert a positive effect on environmental efforts (Anton et al., 2004). The perception of risk associated with physical climate change motivates environmental practices (Thomas et al., 2004). Firms' perception of risk constitutes a fair assessment of their attitude towards CCMT adoption. If the decision makers perceive higher risks from climate change, they will be more proactive in deploying CCMTs to mitigate the problem. We thus expect that the firm's risk attitude toward climate change is positively related to the size of CCMT.

3.2. Management factors and CCMT composition

In this section we study whether specific management factors would motivate the implementation of different types of technologies. Literature has shown that specific management factors can impact firm's technology preference (Cordano and Frieze, 2000). However, to the best of our knowledge, no studies have been done in the context of CCMT. We believe examining the link between management factors and CCMT composition will help the firm design more adequate management policies to meet the climate change challenge.

3.2.1. Drivers of pollution control technologies

Among the five types of technologies, pollution control technologies are less attractive to the management, because they are costly and generally do not offer sufficient economic returns to cover the cost. On the other hand, researchers have pointed out that pollution control technologies, with the installation of end-of-pipe equipment to clean up emissions subsequent to generation, are generally more visible than pollution prevention technologies that are embedded in the operating processes (Berrone and Gomez-Mejia, 2009). Meanwhile, Holmstrom and Milgrom (1991) suggest that monetary incentives may motivate employees to shift efforts to more observable tasks. Pollution control technologies provide a medium for the employees to demonstrate climate friendly activities to reap the monetary incentive. Therefore, we anticipate the provision of monetary incentive is positively associated with the use of pollution control technologies.

King and Lenox (2002) find that firms may intend to display environmental awareness through "end-of-pipe" pollution control. The main objective of displaying environmental awareness is to ease the pressures from policymakers, regulators and customers. In addition, even though pollution control may be economically unappealing, firms under sufficient pressures may still resort to it as a useful approach to control emissions. Therefore, firms perceiving a higher level of risk from climate change are more likely to employ pollution control technologies, either as a means to show environmental awareness or as a last resort to curb emissions. We hypothesize that the firm's risk attitude toward climate change is positively related to the use of pollution control climate change mitigation technologies.

3.2.2. Drivers of eco-efficiency technologies

Eco-efficiency technologies reduce or eliminate the creation of GHG emissions at the source by cutting input energy and/or material use. They improve environmental performance and economic bottom-line simultaneously. Therefore, eco-efficiency technologies have been widely adopted with strong support from the management, even when environment is not on the minds of the management. This resonates with Sharma and Henriques (2005) who

conclude that firms adopt eco-efficiency not due to pressure from external stakeholders such as regulators and customers. Therefore, risk of climate change as perceived by the firms is not likely to be a significant driving force behind adoption of eco-efficiency technologies. As pointed out by prior literature (King and Lenox, 2002), eco-efficiency technologies tend to be complex solutions that involve structural change of existing process, and hence may take longer times to realize the benefits than pollution control technologies. There is also a tradeoff between eco-efficiency and flexibility (Schulze and Heidenreich, 2017). To implement eco-efficiency technologies, the firm may need to surmount more barriers than end-of-pipe pollution control technologies. Therefore, monetary incentive, as an instrument of formal management control, may be an effective instrument to encourage the use of eco-efficiency (Schulze and Heidenreich, 2017).

3.2.3. Drivers of green design technologies

Green design technologies typically entail substantial investments and even fundamental change of the production process. Existing literature has found that external factors such as regulatory and market pressures can drive the introduction and use of green design technologies. Moreover, new design of products necessitates coordinated efforts across different departments and thus would better be supervised by someone with more authority and resources in the firm. The feasibility of green design hinges on approval and support from high-level management. Therefore, we posit that green design is more likely to be used if direct responsibility for climate change is placed on a position higher in the organizational hierarchy of the firm.

3.2.4. Drivers of low-carbon energy technologies

Low-carbon energy sources, such as solar, wind, hydro and biofuel, can supply electricity, fuel, thermal and mechanical energy. While various low-carbon energy sources are projected to play a key role in climate change mitigation, the levelized cost of low-carbon energy (i.e., cost of the energy over its lifetime from generation to consumption) is still higher than prices of conventional energy sources under current technology (Arvizu et al., 2011). Therefore, from a purely economic rationale, low-carbon energy is not a desirable technology. To promote the use of low-carbon energy, policymakers have frequently resorted to regulatory instruments such as usage mandate. Regulatory risk and consumer pressure have traditionally been linked to the investment in low-carbon energy. Therefore, we expect the firm's risk attitude toward climate change is positively related to the use of low-carbon energy technologies.

3.2.5. Drivers of management system technologies

Unlike other technologies, management system technologies, such as GHG monitoring and employees' training programs, are soft measures that do not abate GHG emissions directly. Rather, management system technologies serve as preconditions and provide foundations for further mitigation actions. Since these technologies are specifically targeting at GHG emissions, their economic benefits are limited if not nonexistent. Therefore, a firm that is not seriously engaging with climate change problem is less likely to implement management system technologies. Hence we conjecture the firm's risk attitude toward climate change is positively related to the use of management system technologies.

3.2.6. Determinants of technological diversification

Another important aspect of a firm's technology portfolio is its level of diversification. Firms engage in technological diversification to exploit economics of scope in R&D, improve absorptive capability and technological competence, reduce R&D risk, and

facilitate business or product diversification (Kim et al., 2016). While a great many studies have examined the effect of technological diversification on firm performance, few studies have touched on the determinants behind technological diversification (Chiu et al., 2010). In this study we examine the link between management factors and the diversification of CCMTP.

4. Data and variables

This study utilizes the data on U.S. firms for 2011–2013 from the CDP and COMPUSTAT databases. Although the earliest CDP data dates back to 2003, the survey did not collect technology investment data prior to 2011. Ideally, a longer time horizon is desirable but CDP only provides us the data until 2013. For the purpose of this study, we extract all observations of the U.S. firms over the annual periods 2011–2013 from CDP. This produces a sample of 1135 observations. The sample is then matched with the operational characteristics data obtained from COMPUSTAT. In the matching, we have to remove observations from private firms surveyed by CDP because COMPUSTAT only provides data on publically held firms. We eventually obtain an unbalanced panel of 910 firm-year observations belonging to 362 unique firms. Among them, 248 firms have data for all three years, 52 firms report in two years and 62 firms have only one-year data. The industry and yearly distributions of the sample are summarized in Table A1 in Appendix. Below we describe the variables used in our study.

4.1. CCMTP measures

We model the CCMTP in three different ways, aiming to capture various aspects of the portfolio. The first approach captures the portfolio composition by calculating the proportion of investment in each technology out of the total investment (*PropTech*). This proxy indicates the allocation of capital in one technology relative to others. The second approach is to represent the technology with the absolute amount of capital investment in it (*InvTech*). However, these two measures suffer from missing value problem. In the sample, investments in about 30% of the projects are not reported by the firms. There are several common methods to deal with missing data (Graham, 2009), including removing projects with missing data, dummy variable adjustment for missing data and imputation. In our study, we choose to discard the projects with missing data. This is because upon a close scrutiny of the description of the projects provided by the firms, we find that projects with missing investment data appear to be small in scale and quite insignificant compared to the ones with investment data. For instance, Goodyear reports in CDP 2012 that the firm invests in 10 different energy efficiency projects. The biggest project is to replace existing boilers with more efficient ones, costing 3,102,000\$. Investment in one project is not reported. Goodyear describes the project as “a common initiative for detecting and repairing leaks ... Leak repairs are scheduled during preventive maintenance activities.” Based on the description, we infer that the project is part of routine maintenance and costs significantly less than, say, the replacement of boilers. Most of the projects with missing investment data are similar to the case of Goodyear. Therefore, discarding them is not likely to result in biased results. Note that in doing so, we still preserve the full firm-year sample, i.e., discarding the projects means that the firm's investment in those projects is set to zero.

If the investments on some projects are substantial, ignoring them may be problematic. Hence we come up with a third proxy as a precautionary measure. Specifically, we count the number of initiatives (*NumTech*) that have been undertaken to address climate change based on each technology, regardless of whether

investment is reported or not. Even though the investment-based measures of portfolio seem to be more appropriate, we need the count measure as a complement. Similar count measures have been employed in prior studies (Anton et al., 2004). In a similar manner, we capture the portfolio size with *TotalInv* and *TotalNum*, representing the total investment over all types of technologies and the total count of initiatives over all technologies. We measure the level of diversification as $1 - \text{Herfindahl index}$, i.e., $Diversification = 1 - \sum PropTech^2$ with the summation taken over all types of technologies.

4.2. Management factors

Responsibility. This is the highest level of position that is responsible for climate change policy in the organization. The CDP survey asks the respondent to indicate whether the highest responsibility is delegated to (1) individual/subset of the board or the other committee appointed by the board, (2) senior manager/officer, or (3) other manager/officer such as the sustainability officer. We codify the above answers as 2, 1 and 0 respectively such that a higher value represents a position closer to board.

Incentive. The firm provides no incentive, monetary incentive, and/or non-monetary incentive (typically through internal recognition and award). There are two variables to capture the firm's incentive policy, *Monetary* and *NonMonetary*. *Monetary* is equal to one if the firm provides monetary compensations to managerial positions for climate change performance, and zero if none. *NonMonetary* is derived in the same way.

Risk. A firm's risk attitude toward climate change is constructed through a series of questions on different types of risk associated with climate change. There are three categories of risks: regulation, market, and physical climate change. Each category of risk is further decomposed into subtype of risks. For each subtype of risk, the firm reports the likelihood of the risk, impact of risk on operations and timeframe of the risk. Specifically, the following questions are asked: “Have you identified any climate change risks (current or future) that have the potential to generate a substantive change in your business operations, revenue or expenditure?” “Please describe your risks driven by changes in regulation, likelihood, and magnitude of impact.” We construct a risk measure by multiplying likelihood and impact. The CDP requires respondent to assess likelihood based on an eight-level scale from “exceptionally unlikely” to “virtually certain”. We quantify the answers using integers from 0 to 7, with 0 being “exceptionally unlikely” and “7” being “virtually certain”. If a respondent replies “unknown”, we assign the average value 3.5 to it. The magnitude of the impact of regulation is rated by a 5-level scale from low to high. We let the low magnitude take the value of 1, and the high magnitude take the value of 5, and all other magnitude levels are in between. *Risk* is the product of likelihood and impact averaged overall all risk types. We explore other ways to construct the risk attitude measure in robustness check.

4.3. Controls

We control for factors that might influence adoption of climate change mitigation technologies. Firm size is expected to have a positive effect on the adoption of CCMTs, because larger firms have more resources to undertake climate change initiatives than smaller ones. Also, large firms are generally more visible to policymakers and customers, which may affect their environmental strategy. We control for firm size with the natural logarithmic of total assets (*Assets*, item #6). Prior studies indicate that technological capability of a firm can impact the firm's performance and

use of environmental technology. We include *R&DI*ntensity, measured by the ratio between R&D expense (item #46) and sale (item #12), to proxy the technological capability of the firm. Following the common practice in empirical study, we replace missing R&D expense in COMPUSTAT with zero. Existing research (Anton et al., 2004) shows that age of assets can impact employment of environmental management practices and environmental performance. As in Anton et al. (2004), we define age of the assets (*AgeAssets*) as the ratio between gross assets and total assets, where gross assets is calculated as the sum of total assets and accumulated depreciation and amortization (item #196). Firm leverage is known to affect firm investment decisions and performance. Leverage is calculated as long-term debt (item #9) scaled by total assets. A firm's investment decision may depend on its current carbon emission. Therefore we introduce *CarbonIntensity*, defined as the total direct and indirect emissions scaled by total assets. We also use a binary control variable *Target* to denote if the firm has a GHG emission target in place. The variable is extracted from CDP database. We capture year-specific and industry-specific effects by including the *year dummies* and 1-digit SIC *industry dummies* in relevant models.

Table 1 summarizes the definitions and descriptive statistics of key variables for the full sample. On average each observation employs a total of 5.322 initiatives, with 0.396 of pollution control initiatives, 2.830 of eco-efficiency initiatives, 0.144 of green design initiatives, 0.536 of low-carbon initiatives and 0.366 of management system initiatives. Eco-efficiency technologies account for 41.2% of the total investment, which is the largest share of all technologies. Green design technologies represent 1.3% of the total investment. Monetary incentives, with 62.6% of the observations offering them, are more prevalent than non-monetary incentives, which are available at 42.2% of the observations. **Table 2** shows the correlation coefficients for some of the key variables in the analysis.

Monetary incentive appears to bear a positive association with pollution control technologies. Risk has a positive relation with both pollution control and low-carbon energy technologies. We also find a positive association between responsibility and green design technologies.

5. Empirical analysis

5.1. Methods

Throughout our analysis, we run two types of estimate regressions. The first is a pooled panel regression for the sample of firm-year observations. The second regression utilizes a cross-sectional framework at the firm level with variables aggregated or averaged over 2011–2013. In this regression, we restrict scope to firms that have reported to CDP in all three years, which constitute a sample of 248 firms. Note that in this cross-sectional specification, data for all years are employed but there is only one observation per firm. The cross-sectional regression serves to complement the panel regression. The technology investment over the years may exhibit high volatility caused by reasons unrelated to the independent and control variables, such as inconsistent reporting practices. Using the averaging data can help alleviate this type of problem (Bosworth and Rogers, 2001).

We begin our exploration by showing how the management factors of interest influence the overall investment in climate change technology portfolio. Because the investment data in our sample is skewed to the right, it is log transformed in subsequent regressions. The first estimation employs a pooled ordinary least squares (OLS) regression model with panel-corrected standard errors (PCSE). The PCSE specification enables us to accommodate heteroscedasticity and contemporaneous dependence among investments, and autocorrelation within each firm's investments

Table 1
Description of key variables and summary statistics.

Variable	Description	Mean	Std. dev.
TotalInv	Total investment in all sorts of technologies (unit: \$)	1741477	11665456
TotalNum	Number of all technologies used	5.322	5.420
InvPollCon	Investment in pollution control (unit: \$)	99048	1204372
PropPollCon	Proportion of investment in pollution control	0.048	0.192
NumPollCon	Number of all pollution control technologies	0.396	1.226
InvEcoEff	Investment in eco-efficiency (unit: \$)	1031095	8332362
PropEcoEff	Proportion of investment in energy efficiency	0.412	0.450
NumEcoEff	Number of eco-efficiency technologies	2.830	3.736
InvGreenDesign	Investment in green design (unit: \$)	300842	5371361
PropGreenDesign	Proportion of investment in green design	0.013	0.104
NumGreenDesign	Number of green design technologies	0.144	0.557
InvLowCarbon	Investment in low carbon energy (unit: \$)	106570	1736205
PropLowCarbon	Proportion of investment in low carbon energy	0.101	0.263
NumLowCarbon	Number of low carbon energy technologies	0.536	0.978
InvManageSys	Investment in management system (unit: \$)	1276671	34009574
PropManageSys	Proportion of investment in management systems	0.025	0.119
NumManageSys	Number of management system technologies	0.366	0.779
ROA	Return on assets, net income/total assets	0.058	0.062
CarbonProductivity	Ratio between sales and total scope 1&2 carbon emissions (unit: \$/ton)	372.950	1076.628
Responsibility	Measure of the hierarchical distance between the highest position with direct responsibility for climate change and the board. From low position to high position, take values from 0 to 2.	0.578	0.494
MonetaryInc	Indicator, 1 if firm provides monetary incentive for climate change to its managers and employees, 0 if not	0.626	0.484
NonMonetaryInc	Indicator, 1 if firm provides non-monetary incentive for climate change to its managers and employees, 0 if not	0.422	0.494
Risk	Measure of the risk attitude of the firm toward climate change	2.830	3.736
Assets	Total asset (unit: million\$)	71180	241044
RDIntensity	R&D expense/Sales	0.038	0.067
AgeAssets	Measure of newness of the assets, defined as the ratio between gross assets and total assets	0.829	0.117
EnergylIntensity	Energy expense as a proportion of operating expense	6.701	11.466
Leverage	Long-term debt/Total assets	0.204	0.140
Target	Indicator, 1 if the firm has an emission target, 0 if not	0.678	0.469
ClimateProgram	Indicator, 1 if the firm joins a climate change program, 0 if not	0.327	0.252

Table 2
Correlation matrix.

Variable	1	2	3	4	5	6	7	8	9	10
1 TotalInv	1.00	-0.01	0.04	-0.01	-0.02	-0.01	-0.04	0.03	0.04	0.09
2 PropPollCon	-0.01	1.00	-0.38	-0.05	-0.11	-0.07	0.05	0.03	-0.05	0.13
3 PropEcoEff	0.04	-0.38	1.00	-0.20	-0.54	-0.20	-0.03	-0.02	0.04	-0.15
4 PropGreenDesign	-0.01	-0.05	-0.20	1.00	-0.06	-0.02	0.09	0.02	-0.02	-0.02
5 PropLowCarbon	-0.02	-0.11	-0.54	-0.06	1.00	-0.10	-0.06	0.00	-0.01	0.07
6 PropManageSys	-0.01	-0.07	-0.20	-0.02	-0.10	1.00	0.04	0.01	0.02	0.07
7 Responsibility	-0.04	0.05	-0.03	0.09	-0.06	0.04	1.00	0.15	0.14	0.15
8 Monetary	0.03	0.03	-0.02	0.02	0.00	0.01	0.15	1.00	0.29	0.21
9 NonMonetary	0.04	-0.05	0.04	-0.02	-0.01	0.02	0.14	0.29	1.00	0.18
10 Risk	0.09	0.13	-0.15	-0.02	0.07	0.07	0.15	0.21	0.18	1.00

(Beck and Katz, 1995). Since the PCSE specification requires at least two observations for a firm, we remove 62 firms that have reported only once in the sample and run the regression for the remaining 848 firm-year observations. The regression is as follows,

$$\begin{aligned} \text{Log}(TotalInv}_{it} &= \beta_0 + \beta_1 \text{Responsibility}_{it} + \beta_2 \text{Monetary}_{it} \\ &\quad + \beta_3 \text{NonMonetary}_{it} + \beta_4 \text{Risk}_{it} + \beta_K \text{Controls}_{it} \\ &\quad + \beta_Y \text{Year} + \beta_I \text{Industry} + \varepsilon_{it}. \end{aligned} \quad (1)$$

In (1), i denotes firm and t denotes year. The control variables include logarithm of total assets, R&D intensity, age of assets, leverage, target, and carbon intensity, all sampled at year t . β_K , β_Y , and β_I are vectors of coefficients for the control variables, year dummies and industry dummies. To avoid losing observations that report zero investment, we add a small number 1 to $TotalInv$ in computing logarithm. We also run OLS cross-sectional regressions using the total investment over 2011–2013 as the dependent variable.

As discussed before, representing the technology portfolio with overall investment may generate biased results because of missing investment values for a fraction of climate change initiatives. Therefore, we complement the investment measure with the number of climate change technologies. The number of climate change technologies as the dependent variable is a non-negative integer count number. There are two models to deal with count data, Poisson and negative binomial. Poisson model assumes the conditional variance of the dependent variable is equal to its mean. The negative binomial model is more general, allowing for different mean and variance. We run the over-dispersion test (Greene, 1997) for the choice between Poisson and negative binomial. The test returns a significant statistic ($\chi^2=88.706$) with a p-value far smaller than the 1% level, thus justifying the use of negative binomial model. The negative binomial model is specified as follows:

$$\begin{aligned} \text{TotalNum}_{it} &\sim \text{Poisson}(\lambda_{it}), \\ \lambda_{it} &= \exp(X_{it}\beta + \varepsilon_{it}), \\ e^{\varepsilon_{it}} &\sim \text{Gamma}(1/\alpha, \alpha), \end{aligned} \quad (2)$$

where $TotalNum$ denotes the total number of technologies adopted, X_{it} denotes the vector of explanatory, control and dummy variables as in model (1), and β is a vector of coefficients to be estimated. We also run a cross-sectional regression by aggregating the data. The dependent variable is the total number of technologies employed over 2011–2013 and all other variables are averaged.

Then we examine how the management factors of interests are related to the proportion of investment in each type of technology. We run pooled OLS regressions with PCSE specification as follows,

$$\begin{aligned} \text{PropTech}_{it} &= \beta_0 + \beta_1 \text{Responsibility}_{it} + \beta_2 \text{Monetary}_{it} \\ &\quad + \beta_3 \text{Nonmonetary}_{it} + \beta_4 \text{Risk}_{it} + \beta_K \text{Controls}_{it} \\ &\quad + \beta_Y \text{Year} + \beta_I \text{Industry} + \varepsilon_{it}. \end{aligned} \quad (3)$$

In (3), the dependent variable $PropTech$ denotes the proportion of investment in a specific technology. The control variables are the same as in (1). We also run regressions with the absolute amount of investment as the dependent variable as follows,

$$\begin{aligned} \text{Log}(InvTech}_{it} &= \beta_0 + \beta_1 \text{Responsibility}_{it} + \beta_2 \text{Monetary}_{it} \\ &\quad + \beta_3 \text{Nonmonetary}_{it} + \beta_4 \text{Risk}_{it} + \beta_K \text{Controls}_{it} \\ &\quad + \beta_Y \text{Year} + \beta_I \text{Industry} + \varepsilon_{it}. \end{aligned} \quad (4)$$

Please note in the above formulation, we take a log transformation on the dependent variable $InvTech$ due to right-skewed pattern of investment data. We discuss alternative regression specifications for robustness check in section 5.3.

We run the negative binomial models by taking the number of each technology $NumTech$ as the dependent variable. Since $NumTech$ contains many zeros, the standard negative binomial regression may not be appropriate. Therefore, for each technology we run the Vuong non-nested test (Vuong, 1989) for the choice between standard negative binomial and zero-inflated negative binomial. The test returns significant statistics at the 1% level for pollution control, green design, low-carbon energy, and management system, justifying the use of zero-inflated negative binomial model for those technologies. For eco-efficiency technology, standard negative binomial is used.

We also estimate cross-sectional regressions for the sample of 248 firms. To obtain the proportion of investment, we aggregate the investment in each technology over 2011–2013 and scale it by the total investment. The investment and count measures are obtained by summing up the investment in and numbers of each technology over 2011–2013. For the count measure $NumTech$, the Vuong test suggests zero-inflated negative binomial model except for eco-efficiency technology.

Some technologies may only be feasible in certain industries. Specifically, as pointed out by Kassinis and Soteriou (2003), pollution control technologies are not available for most service firms. Therefore, in studying pollution control technologies, we restrict our sample to manufacturing industries with 2-digit SIC code between 20 and 39 (436 firm-year observations in pooled regression, 123 firms in cross-sectional regression). The green design technologies are only available for firms that produce final goods. Following Anton et al. (2004), we identify relevant firms based on 4-digit SIC code. Specifically, if any firm with a specific 4-digit SIC code reports green design technology, then the firms in the same 4-

digit SIC sector are kept in sample. Otherwise, the whole 4-digit SIC sector will be dropped. We restrict the study of green design technologies to these firms (452 firm-year observations in pooled regression, 126 firms in cross-sectional regression).

Finally, to investigate the determinants of technological diversification, we run the following regression,

$$\begin{aligned} Diversification_{it} = & \beta_0 + \beta_1 Responsibility_{it} + \beta_2 Monetary_{it} \\ & + \beta_3 Nonmonetary_{it} + \beta_4 Risk_{it} + \beta_K Controls_{it} \\ & + \beta_Y Year + \beta_I Industry + \varepsilon_{it}. \end{aligned} \quad (5)$$

5.2. Results

In this section we describe the determinants of the CCMTP. Our results bear important implications for policymakers and firm management who could take the determinants into consideration in building desirable technology portfolios.

5.2.1. Determinants of climate change mitigation technology portfolio size

Table 3 reports the impacts of explanatory variables on total investment and number of technologies from regressions (1) and (2) respectively. Pseudo R^2 is reported for negative binomial regressions and adjusted R^2 is reported for other regressions. As expected, the coefficients for responsibility have positive signs, but the positive relation is significant only for the number of technologies. Therefore, having a higher position of responsibility for climate change in corporate management hierarchy is associated with a higher number of technologies but not necessarily a higher total investment. A plausible explanation is that a higher position in

charge of climate change is likely to coordinate different types of mitigation efforts, so the number of technologies employed by the firm increases. In cross-sectional regressions, coefficient of monetary incentive is positive with $p < 0.1$. In pooled regressions, monetary incentive is positively associated with the total investment and number of technologies and both associations are significant with $p < 0.01$. This provides very strong support for our conjecture that monetary incentive is a powerful tool to encourage the use of CCMTs.

Non-monetary incentive and risk have significantly positive associations with the number of technologies employed in both pooled and cross-sectional specifications. Non-monetary incentive exhibits positive associations with total investment but the relationship is not significant. Risk is also positive for total investment but the strength of linkage is weak. Therefore, the results show non-monetary incentive and risk attitude drive the number of technologies but not necessarily the real investments. When real money is at stake, non-monetary prizes and recognitions do not provide sufficient incentives for the managers to invest in mitigation technologies. It is also noteworthy that coefficient of monetary incentive is larger than non-monetary incentive for total investment. Among the control variables, we find that assets and target exhibit significant and positive associations with total investment and number of technologies in almost all regressions. Age of assets has a significantly negative association with the two measures of CCMTP in pooled regression. Leverage is negatively related to the size of CCMTP. The results with respect to control variables are largely consistent with findings in prior literature (Anton et al., 2004).

5.2.2. Determinants of environmental technology portfolio composition

We next examine the effects of responsibility, incentive policy

Table 3
Overall technology portfolio size.

Dependent variable:	Log(TotalInv)		NumTech	
	Pooled	Cross-sectional	Pooled	Cross-sectional
Constant	2.960 *	-15.179 **	-1.935 **	3.188 ***
	(1.795)	(5.995)	(0.766)	(0.465)
Responsibility	0.074	0.292	0.110 *	0.184 *
	(0.403)	(0.708)	(0.058)	(0.104)
Monetary	1.473 ***	1.161 *	0.178 ***	0.213 *
	(0.426)	(0.712)	(0.063)	(0.123)
NonMonetary	0.565	0.972	0.299 ***	0.191 *
	(0.397)	(0.652)	(0.058)	(0.114)
Risk	0.043	0.091 *	0.013 ***	0.031 ***
	(0.032)	(0.052)	(0.005)	(0.009)
<i>Controls:</i>				
Assets (Log)	0.555 ***	0.850 ***	0.030 ***	0.018
	(0.141)	(0.233)	(0.026)	(0.037)
R&DIIntensity	4.425	1.941	-0.490	-0.850
	(3.279)	(5.568)	(0.579)	(0.850)
AgeAssets	-5.615 ***	-0.554	-1.386 ***	-0.266
	(1.789)	(3.282)	(0.366)	(0.459)
Leverage	-0.143	-0.993	-0.295	-0.610
	(1.467)	(2.453)	(0.265)	(0.400)
Target	1.825 ***	2.225 **	0.249 ***	0.221 *
	(0.441)	(0.907)	(0.085)	(0.135)
CarbonIntensity	0.450	16.748	0.128	0.254
	(0.289)	(4.497)	(0.119)	(0.184)
Year Dummies	Yes	No	Yes	No
Industry Dummies	Yes	Yes	Yes	Yes
N	848	248	848	248
Adjusted/Pseudo R^2	0.111	0.179	0.149	0.094

Standard errors are in parentheses.

Panel-corrected standard errors are reported for the regression in first column.

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

and risk attitude on the technology portfolio composition. The results from pooled regressions are displayed in Table 4. For each technology, we represent it by three measures, the proportion of investment *PropTech*, the logarithm of absolute investment Log(*InvTech*), and the number of initiatives corresponding to the technology *NumTech*. For *PropTech* and *InvTech*, we employ OLS regressions with panel-corrected standard errors. For *NumTech*, we

employ standard negative binomial model for eco-efficiency and zero-inflated negative binomial model for all other technologies. We report the cross-sectional regressions in Table A2 in Appendix.

For pollution control technology, we restrict our sample to the 417 observations in the manufacturing sectors with 2-digit SIC codes between 20 and 39 and at least two data entries in CDP for 2011–2013. This is because pollution control technologies such as

Table 4
Management factors and CCMP composition.

Dependent variable:	Pollution Control			Eco-Efficiency			Green Design		
	PropTech	Log(InvTech)	NumTech	PropTech	Log(InvTech)	NumTech	PropTech	Log(InvTech)	NumTech
Constant	0.231 *** (0.083)	3.528 *** (0.921)	2.280 *** (0.811)	0.082 (0.110)	1.281 (1.031)	-0.009 (0.348)	0.029 (0.019)	0.855 * (0.447)	-0.369 (1.163)
Responsibility	0.002 (0.010)	-0.246 *** (0.091)	-0.162 (0.189)	0.029 (0.020)	0.357 * (0.210)	0.017 (0.078)	0.019 *** (0.004)	0.187 * (0.110)	0.622 ** (0.283)
Monetary	0.029 *** (0.008)	0.664 *** (0.096)	0.476 ** (0.207)	0.077 *** (0.027)	1.296 *** (0.197)	0.169 ** (0.084)	0.005 (0.006)	0.242 *** (0.072)	0.722 ** (0.311)
NonMonetary	-0.012 (0.013)	-0.021 (0.333)	-0.159 (0.184)	0.064 *** (0.016)	0.893 *** (0.221)	0.258 *** (0.077)	-0.009 (0.006)	-0.131 (0.144)	-0.028 (0.256)
Risk	0.002 ** (0.001)	0.065 *** (0.014)	0.062 *** (0.013)	-0.005 *** (0.001)	0.016 (0.016)	0.015 ** (0.006)	0.000 (0.000)	0.012 (0.009)	0.046 *** (0.018)
<i>Controls:</i>									
Assets (Log)	0.008 *** (0.003)	0.138 (0.128)	0.065 *** (0.066)	-0.004 (0.006)	0.418 *** (0.067)	-0.003 (0.027)	-0.001 (0.001)	0.019 (0.031)	-0.017 (0.091)
R&DIIntensity	-0.079 ** (0.031)	-2.655 (1.617)	-5.633 *** (2.035)	0.455 ** (0.191)	3.507 *** (0.500)	0.464 (0.615)	0.041 (0.030)	-0.228 (0.416)	5.708 *** (1.936)
AgeAssets	-0.328 *** (0.090)	-5.139 *** (1.023)	-4.714 *** (0.788)	0.266 *** (0.066)	-2.659 * (1.540)	0.692 ** (0.352)	-0.017 (0.023)	-1.120 ** (0.468)	-3.327 *** (1.145)
Leverage	-0.067 ** (0.028)	-1.505 ** (0.589)	-0.808 (0.704)	0.054 (0.080)	-0.983 (1.636)	-0.525 ** (0.288)	0.000 (0.030)	-0.417 * (0.231)	-0.828 (1.037)
Target	-0.015 (0.014)	0.127 (0.244)	-0.183 *** (0.207)	0.113 *** (0.034)	1.623 *** (0.492)	0.356 *** (0.089)	0.003 (0.007)	0.128 (0.136)	0.503 (0.329)
CarbonIntensity	0.006 (0.004)	0.215 * (0.127)	-0.101 (0.217)	-0.029 *** (0.009)	-0.311 (0.250)	0.208 (0.093)	-0.004 (0.011)	-0.141 (0.130)	-0.580 (0.488)
Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	417	417	417	848	848	848	423	423	423
Adjusted/Pseudo R ²	0.168	0.104	0.175	0.142	0.144	0.163	0.164	0.132	0.209
Dependent variable:									
Low-Carbon Energy									
Dependent variable:	PropTech	Log(InvTech)	NumTech	Management System					
	PropTech	Log(InvTech)	NumTech	PropTech	Log(InvTech)	NumTech	PropTech	Log(InvTech)	NumTech
Constant	-0.190 ** (0.079)	-2.064 (1.509)	-3.105 *** (0.586)	0.005 (0.034)	-0.208 (1.466)	-1.446 ** (0.654)			
Responsibility	-0.020 (0.016)	-0.208 (0.251)	0.173 (0.131)	0.012 (0.007)	0.206 (0.126)	0.021 (0.148)			
Monetary	0.024 (0.020)	0.587 ** (0.232)	0.121 (0.143)	0.001 (0.007)	0.313 ** (0.131)	0.189 (0.163)			
NonMonetary	-0.009 (0.017)	0.100 (0.214)	0.081 (0.126)	0.000 (0.009)	0.178 (0.218)	0.386 *** (0.145)			
Risk	0.003 (0.002)	0.078 ** (0.032)	0.034 *** (0.009)	0.002 * (0.001)	0.076 *** (0.020)	0.027 ** (0.011)			
<i>Controls:</i>									
Assets (Log)	-0.001 (0.006)	0.235 (0.161)	0.126 *** (0.044)	-0.004 (0.097)	0.010 (0.085)	-0.050 (0.050)			
R&DIIntensity	0.348 ** (0.145)	3.270 *** (1.117)	0.277 (1.065)	-0.124 ** (0.052)	-4.017 *** (1.448)	-0.844 (1.178)			
AgeAssets	0.247 *** (0.058)	0.128 (0.202)	0.479 (0.578)	0.064 (0.046)	0.639 (0.661)	0.979 (0.667)			
Leverage	0.116 ** (0.054)	0.790 (0.667)	0.200 (0.485)	-0.076 *** (0.025)	-1.948 *** (0.505)	-0.659 (0.551)			
Target	0.059 ** (0.023)	0.794 ** (0.397)	0.634 *** (0.164)	0.015 (0.009)	0.311 *** (0.115)	0.101 (0.167)			
CarbonIntensity	0.002 (0.009)	-0.001 (0.170)	-0.240 (0.147)	-0.002 (0.001)	-0.168 (0.116)	-0.299 (0.168)			
Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	848	848	848	848	848	848	848	848	848
Adjusted/Pseudo R ²	0.154	0.142	0.185	0.189	0.194	0.155			

Standard errors are in parentheses.

Panel-corrected standard errors are reported in parentheses for PropTech and Log(InvTech).

*p < 0.1; **p < 0.05; ***p < 0.01.

filters and catalytic converters are usually not readily available for non-manufacturing sectors. As expected, the results show that monetary incentive is positively and significantly associated with proportion of investment in pollution control ($\beta = 0.029$; $p < 0.01$), the amount of investment in pollution control technologies ($\beta = 0.664$; $p < 0.01$), and the number of pollution control technologies adopted ($\beta = 0.476$; $p < 0.05$). Therefore, monetary incentive is likely to spur the investment in pollution control. Consistent with our anticipation, we find the risk attitude toward climate change exhibits significant and positive associations with all three measures of pollution control technologies. This further validates our conjecture that firms perceiving weaker climate change risks are less likely to use pollution control. Overall, because pollution control is not an economically appealing technology, managers need to have monetary incentive or perception of strong risk to overcome the economic barrier to deploy pollution control technology.

With respect to eco-efficiency technology, we find monetary incentive displays significantly positive associations with proportion of investment ($\beta = 0.077$; $p < 0.01$), investment ($\beta = 1.296$; $p < 0.01$), and number of technologies ($\beta = 0.169$; $p < 0.05$). Therefore, we have detected very strong support for our anticipation that monetary incentive spurs investment in eco-efficiency technologies. An intriguing observation is that risk has a positive and significant effect on the number of eco-efficiency initiatives, but a negative and significant effect on proportion of investment in eco-efficiency. The result is further confirmed in cross-sectional regression and robustness check with alternative regression specification. This shows that firms perceiving higher risks from climate change make less investment in eco-efficiency technology relative to total investment. A plausible explanation is that eco-efficiency initiatives functioning by cutting input and waste have their limits in mitigating carbon emissions. There is evidence that the cost of improving efficiency is usually an increasing and convex function of the efficiency level, and hence it is costlier to increase efficiency at a higher efficiency level (Zuberi and Patel, 2017). Therefore, once the efficiency reaches a certain level, it is not beneficiary to further increase the share of eco-efficiency technology in the portfolio. Therefore, firms perceiving higher climate change risk are inclined to use other mitigation technologies that are less economically desirable but more potent in carbon abatement.

For green design technology, we restrict our attention to a sample of 423 observations, where the firm produces some kind of final products and reports to CDP more than once in 2011–2013. We find responsibility is positively and significantly related to all three measures of green design. This indicates that delegating responsibility to higher positions can boost the use of green design. Product design is usually a vital decision made by a company, so design change for the purpose of climate protection is more likely to happen under the guidance of someone with a higher position in the corporate hierarchy. We also find that risk attitude has a positive effect on all three technology measures, but only the coefficient for the count measure is significant. Monetary incentive exhibits positive associations with all technology measures while non-monetary incentive exhibits negative associations, though none of which is significant.

We find mild support for the conjecture that higher risk comes with more use of low-carbon energy. The coefficients of risk for investment and technology count are positive and significant. Monetary incentive has positive effects on all three technology measures and the effect is significant for the amount of investment. Since low-carbon energy generally costs more than conventional energy, without monetary incentive or pressures, firm managers would not be willing to deploy low-carbon energy.

For management system technology, we find responsibility and monetary incentive coefficients are all positive but mostly insignificant. Non-monetary incentive has a significant and positive effect on the count measure of the technology. Risk has significantly positive associations with all three measures.

With respect to control variables, we find age of assets has significant and inverse relations with all three pollution control measures and two green design measures. This suggests that firms with newer assets may be unwilling to invest in pollution control or green design technologies. Mitigation target is significantly and positively associated with use of eco-efficiency and low-carbon energy technologies. R&D intensity is positively related to eco-efficiency and low-carbon energy, but negatively related to pollution control and management system. The inverse relationship between pollution control and R&D resonates with the observation in previous literature that pollution control technologies are mainly off-the-shelf solutions easy to be mounted on existing process (Klassen and Whybark, 1999). Hence firms with weaker research capabilities may be more prone to use pollution control.

We report the cross-sectional regressions in Table A2 in Appendix. The results on key variables of interests are generally consistent with the pooled regressions in term of sign, but the strength of significance for coefficients tends to be slightly weaker.

5.2.3. Determinants of technological diversification

We report the determinants of technological diversification in Table 5. It turns out that none of the management factors exhibit significant impacts on the level of diversification in pooled regression or cross-sectional regression. It might be that technological diversification is not driven by specific management factors but is derived from a very complex mechanism.

5.2.4. Robustness checks

We undertake robustness checks to address potential concerns in previous analysis. The test considers alternative model specifications. In (3), because the dependent variables *PropTech* are bounded between 0 and 1, the coefficients in a least squares estimate would be biased (Greene, 1997). A natural way to address the issue is to use Tobit regression model. Our data do not display a significant concentration of investment of unity in a single type of technology. Therefore, we use a Tobit estimator with truncation at 0. We also use Tobit regression for (4) because *InvTech* is zero for a

Table 5
Determinants of technological diversification.

Dependent variable:	Diversification	
	Pooled	Cross-sectional
Constant	0.697 (0.629)	0.801 (1.841)
Responsibility	0.550 (0.727)	1.264 (1.552)
Monetary	0.233 (0.377)	0.114 (0.115)
Non-Monetary	-0.506 (0.427)	0.216 (0.196)
Risk	0.088 (0.274)	-0.102 (0.128)
<i>Controls:</i>		
Assets (Log)	0.017 (0.029)	0.024 (0.037)
R&D Intensity	-1.194 (2.347)	-0.824 (0.757)
AgeAssets	0.112 (0.251)	0.251 (0.218)
Leverage	-0.202 (0.288)	-0.273 (0.220)
Target	0.056 (0.043)	0.025 (0.028)
CarbonIntensity	-0.132 (0.143)	-0.073 (0.096)
Year Dummies	Yes	No
Industry Dummies	Yes	Yes
N	848	248
Adjusted/Pseudo R ²	0.167	0.183

Standard errors are in parentheses.

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Table 6

Summary of results.

Management factor	Technology portfolio variable	Technology portfolio measure		
		Proportion	Investment	Number
Responsibility	Portfolio size	N/A	0	+
Monetary incentive	Portfolio size	N/A	+	+
Non-monetary incentive	Portfolio size	N/A	0	+
Risk	Portfolio size	N/A	0	+
Monetary incentive	Pollution control	+	+	+
Risk	Pollution control	+	+	+
Monetary incentive	Eco-efficiency	+	+	+
Non-monetary incentive	Eco-efficiency	+	+	+
Risk	Eco-efficiency	-	0	+
Responsibility	Green design	+	+	+
Risk	Low-carbon energy	0	+	+
Risk	Management system	+	+	+

“+” means positive and significant.

“-” means negative and significant.

“0” means insignificant.

number of firms. Please note the independent variable is log transformed. This is because the standard Tobit model assumes normality of residuals but our investment data do not satisfy it. The log transformation approach to address the divergence from normality assumption has been demonstrated in previous empirical research (Papalia and Di Iorio, 2001). Table A3 in Appendix reports the Tobit regression results. The sign and significance of the key variables in Tobit regressions are mostly consistent with those in Table 4. Notably, Risk is significantly negative for the proportion of eco-efficiency investment, further confirming the observation in Table 4 that higher risk is linked with lower relative investment in eco-efficiency.

6. Discussions and conclusions

In this study we examine the impacts of firms' responsibility delegation, incentive policy and risk attitude toward climate change on CCMTP. We summarize the key results in Table 6. We find that delegating the responsibility for climate change to a higher position in the firm is positively associated with the total number of technological initiatives against climate change. But the effect on total investment is insignificant. Probably the different effects are due to the division of responsibilities between approval of the projects by managers and financial assessment of projects by technical professionals. On the other hand, it might imply that assigning responsibility for climate change to higher positions may serve as a public relationship vehicle for the firm to display climate awareness. With respect to the composition of the portfolio, responsibility delegation turns out to be a significant driving force behind the green design technology. The explanation is that new design of product is a decision of utmost importance and high-level managers are more likely to own the resource and authority to push for green design.

Both monetary and non-monetary incentives have positive effects on technology portfolio size. However, whereas non-monetary incentive motivates the number of technology initiatives, monetary incentive motivates both the number and real capital investment into the initiatives. Our results show that when real investment in climate change initiatives is at stake, non-monetary incentive is not a sufficient driving force. Monetary incentive is also an effective approach to support the use of eco-

efficiency and pollution control technologies. The environmental benefits of pollution control technology are easily visible and measurable, but the economic value of pollution control is usually not sufficient to cover the cost. Therefore, managers may need monetary incentive to overcome the economic barriers of implementing pollution control.

The risk attitude toward climate change positively affects the use of pollution control, low-carbon energy, and management system. The positive effect on pollution control technologies is somehow in line with Frondel et al. (2007). Risk also has a positive impact on the use of eco-efficiency technologies measured by the number of projects. However, it negatively affects the share of eco-efficiency technology in the portfolio. Eco-efficiency is deemed as a win-win approach for operational and environmental objectives, since it combines conservation of resource and protection of environment. However, a firm perceiving higher risks from climate change is inclined to allocate resources to more radical approaches other than eco-efficiency.

Furthermore, our study implies that policymakers and firm managers may take the relations between management factors and CCMTP into account to develop a proper mix of technologies and achieve desired operational and environmental outcomes. For instance, policymakers who would like to encourage the use of eco-efficiency technology should be cautious of imposing excessively stringent environmental regulations, because the associated risk can stimulate the firm to reduce the share of eco-efficiency in the portfolio. Similarly, firms that intend to introduce climate-friendly products to the market should consider to delegate the responsibility of climate change to a higher position in the firm hierarchy. For both policymakers and firm management, setting up non-monetary awards and recognitions may not spur the investment in CCMTs in general, but can still be a relatively inexpensive and effective approach to stimulate the use of eco-efficiency technology.

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Appendix

Table A1

Sample distribution by industry and reporting year

Industry (2-digit SIC Code)	Description	No. of observations	Year		
			2011	2012	2013
10	Metal Mining	12	3	4	5
13	Oil And Gas Extraction	30	10	10	10
16	Heavy Construction Other Than Building Construction Contractors	4	1	1	2
20	Food And Kindred Products	56	18	19	19
21	Tobacco Products	9	3	3	3
24	Lumber And Wood Products, Except Furniture	11	3	3	5
25	Furniture And Fixtures	13	4	5	4
26	Paper And Allied Products	24	7	8	9
28	Chemicals And Allied Products	89	29	29	31
29	Petroleum Refining And Related Industries	9	3	3	3
30	Rubber And Miscellaneous Plastics Products	6	2	2	2
33	Primary Metal Industries	9	2	3	4
34	Fabricated Metal Products	9	3	3	3
35	Industrial And Commercial Machinery And Computer Equipment	52	15	17	20
36	Electronic And Other Electrical Equipment And Components	79	23	27	29
37	Transportation Equipment	26	8	8	10
38	Measuring, Analyzing, Controlling Instruments; Photographic, Medical Goods	39	11	13	15
39	Miscellaneous Manufacturing Industries	5	1	1	3
40	Railroad Transportation	9	3	3	3
42	Motor Freight Transportation And Warehousing	5	1	1	3
44	Water Transportation	5	2	2	1
45	Transportation By Air	12	4	4	4
48	Communications	25	7	9	9
49	Electric, Gas, And Sanitary Services	76	25	26	25
51	Wholesale Trade-non-durable Goods	7	1	2	4
52	Building Materials, Hardware, Garden Supply, And Mobile Home Dealers	5	1	2	2
53	General Merchandise Stores	14	4	5	5
54	Food Stores	11	4	4	3
56	Apparel And Accessory Stores	9	3	3	3
58	Eating And Drinking Places	11	3	4	4
59	Miscellaneous Retail	14	5	5	4
60	Depository Institutions	37	11	12	14
61	Non-depository Credit Institutions	9	3	3	3
62	Security And Commodity Brokers, Dealers, Exchanges, And Services	25	8	7	10
63	Insurance Carriers	41	12	15	14
64	Insurance Agents, Brokers, And Service	6	2	2	2
65	Real Estate	8	2	3	3
67	Holding And Other Investment Offices	15	3	5	7
70	Hotels, Rooming Houses, Camps, And Other Lodging Places	7	2	2	3
73	Business Services	63	16	22	25
75	Automotive Repair, Services, And Parking	7	2	2	3
87	Engineering, Accounting, Research, Management, And Related Services	7	2	2	3
Total		910	272	304	334

Table A2

Technology portfolio composition (Cross-sectional regressions, control variables are omitted)

Dependent variable:	Pollution Control			Eco-Efficiency			Green Design		
	PropTech	Log(InvTech)	NumTech	PropTech	Log(InvTech)	NumTech	PropTech	Log(InvTech)	NumTech
Responsibility	0.065 (0.118)	1.714 (2.633)	0.050 (0.337)	0.018 (0.097)	1.164 (0.971)	0.121 (0.143)	0.205 (0.193)	3.208 (5.436)	0.947 ** (0.483)
Monetary	0.058 (0.116)	2.582 (2.589)	0.431 (0.340)	0.003 (0.096)	1.696 * (0.962)	0.185 (0.143)	0.123 (0.193)	3.034 (5.528)	0.747 (0.487)
NonMonetary	-0.014 (0.101)	0.704 (2.290)	0.006 (0.304)	0.032 (0.086)	1.262 (0.883)	0.241 * (0.131)	-0.153 (0.162)	-2.718 (4.719)	-0.001 (0.411)
Risk	0.013 ** (0.007)	0.495 *** (0.169)	0.090 *** (0.022)	-0.005 (0.007)	0.100 (0.070)	0.024 ** (0.010)	0.006 (0.012)	0.407 (0.341)	0.050 * (0.030)
N	123	123	123	248	248	248	126	126	126
Adjusted/Pseudo R ²	0.188	0.092	0.124	0.121	0.089	0.085	0.148	0.105	0.148

Dependent variable:	Low-Carbon Energy			Management System		
	PropTech	Log(InvTech)	NumTech	PropTech	Log(InvTech)	NumTech
Responsibility	−0.133 (0.096)	−1.003 (1.702)	0.083 (0.229)	0.100 (0.082)	2.075 (2.593)	0.297 (0.254)
Monetary	0.023 (0.095)	2.588 * (1.415)	0.159 (0.233)	0.082 (0.081)	2.636 (2.595)	0.157 (0.255)
NonMonetary	0.087 (0.085)	2.346 (1.547)	0.295 (0.207)	−0.054 (0.070)	0.940 (2.258)	0.382 * (0.228)
Risk	0.009 * (0.006)	0.264 ** (0.116)	0.028 * (0.015)	0.007 * (0.004)	0.416 ** (0.170)	0.027 * (0.015)
N	248	248	248	248	248	248
Adjusted/Pseudo R ²	0.133	0.092	0.105	0.079	0.051	0.073

Standard errors are reported in parentheses.

*p < 0.1; **p < 0.05; ***p < 0.01.

Table A3

Robustness check: Tobit panel regressions for technology portfolio composition

Dependent variable:	Pollution Control		Eco-Efficiency		Green Design		Low-Carbon Energy		Management System	
	PropTech	Log(InvTech)	PropTech	Log(InvTech)	PropTech	Log(InvTech)	PropTech	Log(InvTech)	PropTech	Log(InvTech)
Constant	1.133 ** (0.551)	1.355 (9.003)	0.410 (0.335)	−4.794 * (2.820)	−0.923 (0.775)	−34.084 (18.814)	−1.724 *** (0.422)	−32.673 *** (6.546)	−0.701 ** (0.335)	−29.200 *** (8.634)
Responsibility	−0.091 (0.120)	−1.340 (2.037)	0.044 (0.073)	0.676 (0.626)	0.179 (0.175)	2.817 (4.189)	−0.131 (0.085)	−1.139 (1.329)	0.044 (0.072)	1.117 (1.848)
Monetary	0.166 ** (0.066)	5.795 (2.315)	0.007 (0.079)	2.229 *** (0.670)	0.133 (0.187)	5.818 (4.633)	0.024 (0.095)	2.781 * (1.474)	0.026 (0.080)	3.058 (2.045)
NonMonetary	−0.206 * (0.116)	−2.112 (1.986)	0.115 * (0.069)	1.377 ** (0.612)	−0.236 (0.161)	−4.300 (3.930)	−0.004 (0.082)	0.321 (1.292)	0.036 (0.068)	2.017 (1.754)
Risk	0.026 ** (0.009)	0.511 (0.146)	−0.016 *** (0.006)	−0.022 (0.050)	0.010 (0.012)	0.315 (0.289)	0.013 ** (0.007)	0.290 *** (0.101)	0.014 *** (0.005)	0.418 *** (0.132)
Controls:										
Assets (Log)	0.045 (0.043)	0.610 (0.720)	−0.026 (0.025)	0.517 ** (0.215)	0.029 (0.059)	0.728 (1.402)	0.017 (0.029)	0.835 * (0.454)	−0.011 (0.024)	0.083 (0.608)
R&D Intensity	−1.893 (1.194)	−30.321 (20.716)	0.360 (0.556)	9.418 * (4.980)	0.794 (1.288)	16.830 (31.998)	0.382 (0.651)	12.032 (10.539)	−0.953 * (0.557)	−20.815 (14.588)
AgeAssets	−2.734 *** (0.539)	−38.729 (8.924)	0.920 *** (0.325)	−2.151 (2.793)	−1.259 * (0.751)	−31.680 ** (18.026)	0.890 ** (0.396)	5.203 (6.053)	0.414 (0.326)	7.571 (8.162)
Leverage	−0.575 (0.460)	−10.150 (7.826)	0.211 (0.269)	−1.423 (2.282)	−0.477 (0.644)	−15.611 (15.765)	0.223 (0.326)	0.900 (5.072)	−0.722 ** (0.289)	−19.420 *** (7.463)
Target	−0.104 (0.135)	1.390 (2.285)	0.080 (0.083)	2.876 *** (0.700)	0.267 (0.221)	8.827 (5.395)	0.162 (0.101)	3.014 * (1.542)	0.019 (0.082)	2.277 (2.076)
CarbonIntensity	−0.123 (0.155)	2.960 (2.457)	−0.257 (0.099)	1.255 (0.755)	−0.046 (0.215)	4.155 (5.104)	0.300 ** (0.121)	6.659 *** (1.756)	−0.083 (0.097)	0.708 (2.296)
Year Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Industry Dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
N	436	436	910	910	452	452	910	910	910	910
Pseudo R ²	0.168	0.104	0.142	0.144	0.164	0.132	0.154	0.142	0.129	0.114

Standard errors are reported in parentheses.

*p < 0.1; **p < 0.05; ***p < 0.01.

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